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AUTHOR Barnes, Marianne Betkouski; Conklin, Kathy
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ABSTRACT

This paper contends that the science education community would benefit from a three-step, research-based model that would allow science education researchers, in the final step, to make recommendations to classroom teachers. The first step would be to establish an interdisciplinary approach to research on how the brain and mind learn and remember. By collecting and consolidating available data and engaging in dialog with researchers in other fields, it is argued that the determination can be made as to what data are pertinent to educational needs. At that point researchers in science education would be ready for the planning of educational research based on comprehensive theory. These research results could then lead to the third step, the outlining of actual classroom implications. All three steps must be dynamic and open to new findings. This paper is intended to provide a stimulus for the outlined three-step approach by providing a short history of cognitive science research, by documenting the need for interdisciplinary studies, and by providing a review of current information available on memory systems from research in the cognitive sciences. An extensive bibliography is appended. (TW)

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A REVIEW OF MEMORY SYSTEMS AND IMPLICATIONS FOR RESEARCH INTO THE LEARNING PROCESS*

Marianne Betkouski Barnes
University of North Florida
Jacksonville, Florida 32216

Kathy Conklin
Duncan U. Fletcher Senior High School
Neptune Beach, Florida 32233

National Association for Research in Science Teaching

Lake Ozark, Missouri

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> I sometimes feel in reviewing the evidence for localization of the memory trace, that the necessary conclusion is that learning is not possible. (Lashley, 1950)

In order to make classroom teaching more effective, educational research must provide teachers with scientifically based theory upon which to make pedagogical decisions. Teachers do not have sufficient current information about how their students actually learn and remember.

The most significant widespread influences on science education research into the processes of science reasoning have been those based on Piagetian theory. However, difficulties in designing instruments based on the Piagetian stages of development have left us with conflicting results related to reasoning abilities of various groups of students. Indeed, Lawson (1985), in summarizing research on formal reasoning and science teaching, indicates that "we appear to be left with an interrelated set of reasoning patterns but with no generally accepted model to either describe its nature or explain its development" (p.608). Piaget's contributions to learning theory, especially regarding the notion of schemata, have influenced the modern

cognitive science movement. Although some attempts have been made to interrelate Piagetian stages to information processing theory (Case, 1982), we are now at the point where we must broaden the theoretical base from which we operate to include contributions from cognitive psychology, neuroscience, and other areas which probe into the workings of mind and brain.

However, we are not ready, at this point, to make definitive recommendations regarding how teachers should adapt their methods of classroom teaching. Wittrock (1981) warns against direct translation of neuroscience and cognitive science findings into educational implications. He argues that these fields can help to build models which in turn will guide educational researchers into designing more enlightened approaches to studying knowledge acquisition. "Precisely because neuroscience, behavioral science, and educational research study different levels of related phenomena, research on the human brain can provide useful analogies, suggest new hypotheses, revise old theories, and even eliminate some otherwise attractive but unproductive ideas about teaching and learning" (p.12).

There is an enormous volume of information available concerning brain, memory, and learning. Research findings come from many and varied fields, but research from one field has failed to incorporate and integrate results of similar research in other fields. We must avoid using this large, diverse body of dissociated research to give teachers

conflicting approaches to how their students learn and remember.

The science education community would benefit from a three-step, research-based model that would allow science education researchers, in the final step, to make recommendations to classroom teachers. The first step is to establish an interdisciplinary approach to research on how the brain and mind learn and remember. By collecting and consolidating available data and engaging in dialogue with researchers in other fields, we can determine what data are pertinent to educational needs. Only then will we be able to approach the second step, the planning of educational research based on comprehensive theory. These research results can then lead to the third step, the outlining of actual classroom implications. All three steps must be dynamic and open to new findings.

In this paper we will provide a stimulus for the outlined three step approach by providing a short history of cognitive science research, by documenting the need for interdisciplinary studies, and by providing a review of current information available on memory systems from research in the cognitive sciences.

History of Cognitive Science

Gardner (1985) summarizes the history of the beginnings of cognitive science. The separation from behaviorism, the beginning of scientific studies of the brain, and the birth of cognitive science is said to have begun in 1948 at the

Hixon Symposium at the California Institute of Technology. There speakers like psychologist Karl Lashley "laid out a new agenda for research" (p.11) to provide theories "of human activity that would account for complexly organized behaviors like speaking or playing tennis" (p.12). The Hixon Symposium participants challenged the basis of neurobehaviorism and introduced, in its place, the idea of brain as a computer. In 1950 Alan Turing suggested that a machine could be programmed so that it would not be possible to discriminate the machine answers from those of a human being. Scientists began to contemplate the possibility of building a computer to think like a human.

Less than 10 years after the Hixon Symposium, brain information processing had clearly moved from a new, revolutionary idea to a well-accepted cognitive science. At the Symposium on Information Theory at the Massachusetts Institute of Technology in 1956, linguists implied that language has a precision akin to mathematics. Also at this symposium George Miller (1956) introduced the theory of a 7 unit (chunk) short term memory in humans. In 1958 John von Neumann's book, The Computer and the Brain was published and Donald Broadbent introduced flow charts for cognitive processing. In 1960 Bruner and Miller founded the Harvard Center for Cognitive Studies.

Shortly thereafter psychologist Ulric Neisser (1967) published Cognitive Psychology. In his book he accepts the ideas of brain accession, processing, and transformation of

data, but implies that human brains cannot be compared exactly to computers, as humans are far less "single minded, undistractable, and unemotional" (cited in Gardner, 1985, p.33). In 1968 Richard Atkinson and Richard Shiffrin introduced the concepts of long-term and short-term memories. Finally in 1975, the New York-based Alfred P. Sloane Foundation gave final credence to cognitive science by committing 20 million dollars to research in cognitive science to "discover the representational and computational capacities of the mind and their structural and functional representation in the brain" (cited in Gardner, 1985, p.36). The foundation report indicated interrelationships among 6 fields: philosophy, linguistics, anthropology, neuro-science, artificial intelligence and psychology. These fields would form the intrastructure of cognitive science.

In the years since 1975, the studies of the brain have extended to even more areas of research, including biochemistry, neuroanatomy, phylogeny, pharmacology, experimental and clinical neuropsychology, animal development, psychophysiology, psychopathology and hypnosis. During the 1980's there has been a splintering of the field of cognitive psychology (Gardner, 1985). The models are many and divergent, resulting in apparent contradictions.

Interdisciplinary Efforts

Hence, there is a strong need to consider several models and to consolidate findings before basing educational strategies on limited approaches. Since science education

researchers alone cannot interpret research from diverse fields, the actual interactions with experts in these fields before designing research is essential. Betkouski and Peterson (1985) have described the workings of network in the California university system and in a Northeast Florida setting. The number of studies of memory alone is enormous. Schacter (1984) explains: "Yet in spite of the impressive amount of data and theory generated in the individual areas of memory research, the level of cross-disciplinary communication has been relatively limited. A systematic multidisciplinary attack on problems of memory has not yet emerged" (p.13).

One reason for lack of multidisciplinary cooperation is lack of agreement about which issues are important theoretically. Islands of isolated research have emerged. Baddeley (1985) proposes the following question and solution: "How can we avoid becoming prisoners of our methods? I would suggest that one effective antidote is to move out of the laboratory from time to time and attempt to apply our theories and techniques to practical problems" (p.225). It would behoove educational researchers to review current findings out of memory research and elucidate the contexts alluded to by Baddeley.

Benefits of collaboration are described by Luria and Squire. According to distinguished Soviet psychologist A.R. Luria (1973):

"The attempt to determine the cerebral basis of a

particular human mental process must be preceded by a careful study of the structure of that psychological process whose cerebral organization it is hoped to establish and by identification of those of its components which can be classed to some extent among definite systems of the brain" (p.34). Squire (1982) further validates the need to gather information about behavior as the nervous system is studied.

"While technological advances in the neurosciences make feasible ever more detailed analysis of the nervous system and its parts,it is useful to remember that to know about the function of the nervous system entails understanding of the behavior that it subserves."

The following is a review of selected aspects of memory research from neuroscience and cognitive psychology. Original sources as well as review articles are included in order to provide the reader with an extensive bibliography.

A key element which has been missing in the cognitive sciences is input from educators who are in the unique position to provide valuable information about behavior in classroom settings. We would hope that the information in this review stimulates science educators to become active members of interdisciplinary networks studying cognition.

Sources of Data

Neuroscientific findings related to memory include results of studies with invertebrates, such as Aplysia and Hermissenda; with vertebrates, such as the rabbit, rat, and cat; and with primates. The most pertinent information related to human memory comes from studies of people with amnesia arising from viral infection of the brain, trauma, vascular disorders, alcoholism, and Alzheimer's disease. Other sources of information used by cognitive scientists are studies of normals in situations where they recollect particulars of events, such as eyewitness reports, where their rates of forgetting are determined, and where their memory dependence on age is studied. Other fields, such as artificial intelligence, attempt to build working models of memory processes.

Kinds of Memory

Most current models of memory describe it as several interacting stores and/or systems, rather than as a single unit. In amnesic studies alone, the variations in memory performance has led to doubt that there can be a single category of memory (Cohen, 1984). There are several distinctions among different kinds of memory, each producing a corresponding model of how we remember.

Some of the earliest efforts to define separate memory systems have designated various memory stores. These memory stores are generally named sensory memory, short term

memory, and long term memory. There has been considerable research to determine or describe their nature and location. These stores have been distinguished by their capacity, rate and mechanisms of forgetting, and their coding characteristics (Craik, 1984).

Sensory memories occur at the sensory level and are not noticed as conscious memories. Such memories include visual and auditory storage. A visual sensory memory will be processed when a subject is shown a visual display for .50 msec, for example (Anderson, 1980). Sensory memory is called preattentive memory because the subject will process the information without his attention being given to the information. However, preattentive, sensory stores decay quickly. While the sensory store can hold large amounts of information, tests indicate that this information is held for 5 sec. or less (Kroll, 1975).

Short term memories are transient memories. Information stored in short term memory is in an active state. If the information is not kept active, it is forgotten. There are connections between long term and short term memory, but transfer of information to the long term memory will occur only if it is actively held in the short term memory. Also, for cognitive processes to occur, knowledge necessary for performing the processes must be in the short term memory (Anderson, 1980). At least a few seconds duration is required to process information into short term memory. Information may be retained in short

term memory for a few minutes or for several hours or days, depending upon rehearsal or training (Squire, 1975). However, according to the Peterson Paradigm, studies with subjects remembering trigrams indicate that short term memory decays in only 18 sec. if there is no rehearsal (Peterson & Peterson, 1959).

Short term memory can hold only a limited amount of information at one time. Miller (1956) proposed that people can process 5 to 9 items in short term memory at one time. Miller introduced the term "chunk" to describe the items or bits being processed. Further studies indicate that chunks may be multi-itemed so that the number of items remembered may not be the same as the number of units or chunks (Buschke, 1984).

Within short term memory, two other memories have been designated. Primary memory is the storing of small amounts of material briefly and retrieving the information unchanged, e. g., recalling the last few words in a list. Working memory is storing the same information briefly, but transforming it before giving a response, such as recalling the last few words in a list in their reverse order (Craik and Rabinowitz, 1984).

There is concern with how information comes into the short term store. Information passes from the sensory store into the short term memory store by a process that is not yet completely clear. A problem with direct transfer from the sensory store into the short term store is that of

transferring information without attention into information about which we are conscious. According to Stern (1985) the dilemma which must be solved is how we become conscious of information that we have not identified. He, therefore, proposes, along with others, a revised model of human information processing in which information in the sensory store arouses long term memory so that an appropriate long term memory can be retrieved for recognition of the sensory store. The link, therefore, between long term and short term memory in the revised model is circuitous. In Stern's model there is constant interaction between short and long term memories.

Long term memories are those that endure, perhaps for a life time, although the duration of long term memory is still being researched. Long term memories are stored in nodes or clusters of related ideas. If parts are activated, all are likely to be affected. The node connections represent meaningful associations (Anderson, 1980). Studies have caused researchers to also identify several other kinds of memory within long term memory. Ryle (1949) differentiated "knowing how" from "knowing that", where "knowing that" requires attention in order to remember, while "knowing how" involves action or skills that do not require attention to recall (Cohen, 1984). Bruner (1969) distinguished "memory with record" and "memory without record", where memory with record consists of memories of everyday life while memory without record is memory that

changes skills or operating rules (Cohen, 1984). Researchers studying amnesia and artificial intelligence have established similar distinctions within long term memory. They define memory for procedural knowledge and memory for declarative knowledge (Winograd, 1975; Winston, 1977; Squire, 1982; Cohen and Squire, 1980; Anderson, 1980, 1981, 1982). Procedural knowledge comprises skills we know how to perform such as riding a bicycle; declarative knowledge comprises the facts we know, such as the date of Washington's birthday (Anderson, 1980).

Other categories of long term memory are described as episodic and semantic (Tulving, 1972; Kinsbourne and Wood, 1975; Buschke, 1977; Cermak, Reale, and Baker, 1978; Warrington and Weiskrantz, 1982; Schacter and Tulving 1982, 1983; Wood, Ebert, and Kinsbourne, 1982; Cermak, 1984). Episodic memory is autobiographical memory for specific temporally dated and spatially located events, such as your first day in school. Semantic memory is context--free knowledge, such as facts, concepts and generalizations (Cohen, 1984).

While researchers continue to pursue more information on memory stores and systems of memory, others have determined that it may be more important to concentrate on developing mental processing models and investigating encoding and retrieval processes (Craik and Lockhart, 1972; Jacoby, 1984). Schacter (1984) lists researchers whose works have led to long-term memory distinctions. The

several research fields represented in Schacter's list are the following: experimental psychology (Herrmann, 1982; Johnson, 1983: Schacter and Tulving, 1982; Tulving, 1972, 1983); neuropsychology of amnesia (Cohen and Squire, 1980; Kinsbourne and Wood, 1975, 1982; Moscovitch, 1982; Warrington and Weiskrantz, 1982), animal memory, (Olton, Becker and Handelmann, 1979), artificial intelligence (Winograd, 1975), hypnosis research (Kihlstrom, 1980) developmental studies of both humans (Nelson and Brown, 1978; Schacter and Moscovitch, 1984) and animals (Nadel and Zola-Morgan, 1984).

Processes of Memory

Memory failures are no longer considered to be only reduced capacity of stores, such as short term memory. Many researchers agree that the ways memories are processed may be more important than the location or capacity of a memory store; however, not all agree on how memory processes occur. Tulving and Thomson (1973) argue that storage and retrieval are not independent: "... only that can be retrieved that has been stored... how it can be retrieved depends on how it was stored" (p. 357).

Studies of amnesics have produced different ideas on origins of memory deficits. Deficits are considered to be caused by improper encoding, retrieval or storage of information (Jacoby, 1984). Work on amnesia has led to questions about whether the condition involves a memory

storage deficit, a memory retrieval deficit, or perhaps a combination of the two deficits. A key question is whether memory changes with passage of time. When cues seem to effect the eliciting of information in amnesics, the retrieval theory is reinforced. Also studies of M.D., a stroke victim with aphasia, indicate problems in retrieval that prevent him from remembering the names of fruits although he can recognize and describe them (Alper, 1986). However, there is also evidence that a deeper encoding and consolidation problem may be involved, giving credence to the memory storage position. The memory consolidation position is based on evidence that memory changes with time after learning (Squire, 1982). Memory consolidation is a long-term, ever-changing process; that is, memories change for a long time after initial learning. Squire gives evidence that consolidation is a vital ingredient in memory in the case of the famous amnesic H.M. H.M can remember all memories up to 3 years prior to the onset of his amnesia. However, the time just before his surgery as well as all events since the surgery he cannot remember. This may indicate memories formed before the surgery did not have time to be consolidated.

In 1972, Craik and Lockhart proposed a "depth of processing" model. The significant memory event in this model is the encoding process. They proposed that the strength of memory depends on the depth of processing, where depth is the degree of cognitive analysis. Memories endure

when the information is meaningful. A few unrelated words will not be processed at as deep a level as a meaningful sentence.

Also, in 1972, Tulving had described episodic and semantic memories, followed soon after by his encoding specificity principle. His ideas concerned the importance of encoding processes in episodic memory (Tulving and Thomson, 1973). Tulving stated that memory of an event depended upon what he called a trace (information about the event stored in memory) and a cue (information available at the time of remembering). There must be both trace and cue, and they need to be compatible for retrieval. The trace depends upon encoding operations (Tulving, 1972, 1974, 1979, Tulving and Thomson, 1973). Tulving felt the "depth of processing" model neglected the importance of retrieval conditions (the cue).

In 1977, the "depth of processing" model was modified (Fisher and Craik, 1977). Remembering must include depth of processing and a relationship between encoding operation and retrieval cues. Also, Jacoby and Craik (1979) indicated that equally important to depth of processing were elaboration in encoding and distinction of the new information. Retention depends upon how much you elaborate upon the new information and upon whether or not the new information is discriminable from previously stored, related information.

There persist varying ideas concerning the importance of encoding or retrieval processes in memory. Cermak (1979), based on experiments with Korsakoff patients (a type of amnesic patient), stated that retrieval depends upon different levels of analysis during encoding. Deficiencies in encoding seem to cause memory deficit. There is, however, evidence (Weingartner, 1978; 1984) that at least some memory failures are retrieval failures. Use of certain drugs enables subjects to retrieve memories that otherwise cannot be remembered in free recall. Since 1977 some researchers (Jacoby and Craik, 1979; Tulving, 1979; Jacoby, 1984) have implied that encoding and retrieval processes are essentially the same and cannot be effectively studied separately.

Kintsch (1979) proposed a parallel processing model. He suggested that processing operations may occur in parallel with interaction among levels of processing, rather than sequentially in levels or depths as described by Craik and Lockhart. The idea of parallel processing or inspecting all items simultaneously rather than one at a time had been suggested by Sternberg (1966) and reinforced by others (Sperling, 1970; Wickelgren, 1977).

Locations of Memory

While researchers seek models for processing of memory, other researchers seek the location of memory. Since the days when the neuropsychologist, Karl Lashley, began a

search for the engram, the elusive learning and memory trace in the brain, a debate has ensued about whether memory is localized or distributed across the brain. Lashley (1950) found, in working with the rat brain, that injury to the brain cortex dulled but did not eradicate memory. A type of "mass action" seems to occur in which loss of some cells makes for a less sharp memory. Neuroscientist Karl Pribram (1971) explains this phenomenon by using an analogy to a hologram, a three-dimensional image produced by having unfocused laser beams hit a photographic plate. Each chip holds the whole image; loss of some chips creates a hazier image (Ornstein and Thompson, 1984).

Should the conclusion be that the entire brain is involved in memory and localization is not important? According to neuroscientist Richard Thompson (1982), that inference is not warranted. His work with simple forms of procedural learning supports the assertion that at least some parts of the memory circuit must be localized. Specifically, Thompson and associates found that the cerebellum controls the conditioned eyelid response in rabbits (McCormick, et. al., 1982). Furthermore, Rolls (1984) points out that in studies with monkeys evidence indicates that different kinds of memory are separate and localized in various areas of the brain, such as stimulus-reinforcement associations in the amygdala, recognition memory in the midline thalamus, and recency memory in the prefrontal cortex-inferior temporal visual cortex.

There is also much evidence that memories are transported by brain structures that do not serve as storage sites (Mishkin, 1978; Squire, 1982). Bilateral lesions of the amygdala and hippocampus (temporal lobe) cause memory deficits as are observed in amnesics, such as the well-documented case of H.M (Scoville and Milner, 1957). Also, diencephalon (thalamus) damage in Korsakoff Syndrome causes memory deficits (Huppert and Piercy, 1979; Squire, 1981). Similar deficiencies in monkey brains produce similar results, indicating that the amygdala, hippocampus, and thalamus are all part of a neural-memory system (Mishkin, 1978; Zola-Morgan, 1984).

The chief difference between diencephalic and temporal amnesia can be attributed to deficits in different stages of information processing. The thalamus is involved with memory at short intervals, early processing or encoding. The hippocampus is involved in longer interval memory or storage (Huppert and Piercy, 1979; Squire, 1981; Winocur, 1984). Squire, Cohen, and Nadel (1982) proposed the medial temporal lobe takes part in the process of memory consolidation. However, the information is stored throughout the neocortex. There are also researchers presenting the idea that the hippocampus is involved only in contextual learning or learning of declarative knowledge (Kesner and Di Mattia, 1984; Kubie and Ranck, 1984).

Several neurological models for memory have been described by neuroscientists (O'Keefe and Nadel, 1978;

Mishkin, 1982; Halgren, 1984; Goldberg, 1984; Grossberg, 1982).

Influences on Memory

Particular facets of encoding and retrieving memories are being studied by researchers. Concerns such as cueing, elaboration, attention, and rehearsal are important in forming memories. Also, factors such as aging, emotion, and effect of experience on past memories may influence the forming of new memories.

Cues seem to act to emphasize relationships in stored information (Mandler, 1985). Retrieval depends on organizational structure of memory and this depends on the organization of the encoding (Tulving and Thomson, 1973). The organization of encoding is aided by cues. However, what is not clear is the cognitive and neural mechanisms of the cue. Cues improve recall in amnesics (Warrington and Weiskrantz, 1970; McDowall, 1979). Cueing eliminates some problems of divided attention that plague aging people in episodic memory (Craik, 1984).

Elaboration is a quantitative change in encoding that adds information to the trace (Jacoby and Craik, 1979). The access routes to schemata in memory depend upon the relationship between the schema and other mental contents. It is easier to access a schema if there is greater elaboration. Elaboration provides more access pathways to the schema (Mandler, 1985).

Attention is the initial step in the process of taking in information to be processed. When attention is divided, ability to recall is impaired (Rabinowitz, et. al., 1982). Current attention theories fall into two classes: early selection theories and late selection theories (Mandler, 1985). Early selection theories are described by Broadbent (1958) and Treisman (1964, 1969). Early selection is a form of top-down processing where we select parts of what we perceive for remembering and filter out the others. Late selection theories by Deutsch and Deutsch (1963) and Schiffrin and Schneider (1977) indicate we take in all available evidence and then select the relevant aspects.

Rehearsal is essential for procedural memory. There are three stages needed to form a procedural memory. First is a declarative stage where the task needs to be clearly presented. The second stage is an associative stage where error patterns need to be detected. The third stage is a practice stage where rehearsal must occur with appropriate spacing and in varying contexts (Anderson, 1982).

With aging there occurs concern about loss of ability to effectively retrieve certain kinds of memories. Craik (1984) says that reduced processing abilities of older people often cause them to fail to carry out effective encoding and retrieval operations. Divided attention appears to be a critical problem that can be alleviated by the use of appropriate cues.

The powerful effects of emotion on memory have been substantiated in a number of studies (Bower, 1981). Findings are that we tend to remember better when we are in the same frame of mind (happy, sad, etc.) as we were when we first experienced an event. We often remember minute details of emotionally charged events.

Hall and Loftus (1984) speak to the issue of remembering details of events. In studies with eyewitnesses, they have found that memories change. They conclude that new memories are formed from parts of existing memories and parts of current experience. Each new memory is not a trace of a single experience, but a synthesis of information from different experiences and different times.

Cellular Anatomy and Physiology of Memory

Beyond the efforts to locate memory in the brain, there is much research concerning how memories are formed. Memories appear to be formed as neurons change. New experiences may cause neuronal changes (Woody, 1982).

Short term memories occur when certain nerve pathways are stimulated repeatedly in a short interval resulting in increased neuron conductivity. Appropriate changes in the concentrations of potassium and sodium inside and outside the neuron membrane can increase neuron conductivity. As the membrane is depolarized, calcium ions enter synaptic terminals, causing the release of synaptic transmitter substances. The modulation of calcium ion concentration by

neurons has a time course of minutes, giving chemical synapses a short-term memory (Kandel, 1981).

Studies of long-term memory formation are conducted at the single cell activity level, the interneuronal synaptic activity level, and interconnecting neuron assembly levels. On the single cell level, it seems that the repeated stimulation of neurons causes protein build-up on receiving neuronal membranes. Greenough, et. al (1978) showed neuron activity in rats caused a build-up of amino acids in neuron cell bodies. Kandel and colleagues have shown that protein synthesis is necessary for long-term memory in the marine snail Aplypia (Barnes, 1986).

The synapses between neurons are important in memory formation. Models for learning presented at the Daklem Conference on neural bases of learning in West Berlin show increased calcium in neurons causes changes in synaptic transmission. Neuro-transmitters stimulate protein phosphorylation that may cause long-term changes in protein synthesis and neuron structure (Barnes, 1986). Long-term potentiation, noted by Bliss and Lomo (1973) is a widely studied phenomenon. Long term potentiation is enhancement of synapses by stimulating afferent neurons at high frequency (Morris and Baker, 1984). Most research on long term potentiation has been on pyramidal tract neurons of the hippocampus. Routtenberg (1984) emphasizes that the neuron storage site in the hippocampus may be in CA3 pyramidal

cells, and that storage is enhanced by synapses onto the CA3 cells.

Fuster (1984) states "memory resides less in neurons than in relationships between neurons" (p.285). The changes in structure of dendrites, numbers of dendrites and strength of dendritic synapses are part of building neuron assemblies and are important in memory and learning. Squire (1982) indicates that the nervous system has enormous capacity for plasticity. Plasticity is changeability. Evidence of this plasticity is given by phenomena such as collateral sprouting, competition at synapses, growth of dendrites in response to rich environment, and recovery of function after brain injury.

Trubatch and colleagues (cited in Esler, 1984) have found thickening and shortening of neuronal dendrites when brains of frogs are stimulated. This dendritic change seems to enhance conductivity. Researchers have also shown a loss in the number of dendrites with age. The loss of dendrites decreases the ability of neurons to process information (Kandel, 1981). Also, Rosenzweig (1979) demonstrated an increase in the thickness and weight of the cortex of rats when they are kept in a stimulating environment. There were increased numbers of dendrite spines in the stimulated rats' brains.

The strength of dendritic synapses was discussed at the 1985 Daklem Conference. Pasko Rakic reported that immature synapses will stabilize and endure only when the neuron is

active. For synapses to strengthen, a certain threshold must be reached. Also, Daklem scientists explained that a threshold can be achieved when several neurons synapse on the same cell and fire simultaneously. As more cells fire at the same site, there will be more neurotransmitter substances released. And, therefore, there will be a greater influx of calcium; followed by an increase in protein synthesis (Barnes, 1986). Among neurons there will be a kind of competition at the synapses, with some synapses strengthening and some weakening (Squire, 1982; Barnes, 1986).

Gary Lynch and Michel Baudry (cited in Alper, 1986) found, in studies with rats, that when electric pulses are used to induce long-term potentiation, postsynaptic neurons become flooded with great amounts of calcium. This calcium activates an enzyme calpain, which, in turn, causes the breakdown of fodrin, a major structural component of the spines of neuron dendrites. When the protein skeleton is broken down, this allows the dendrite to change shape. This change in dendritic shape seems to be responsible for declarative knowledge acquisition. However, calpain did not seem to play an important role in procedural memory formation. Other tests on rats by Lynch show that protein synthesis in neurons may be more important in procedural memory.

Memory is also influenced by hormones. McGaugh, et. al. (1982) showed epinephrine from the adrenal medulla

influences retention. Adrenergic hormones apparently work through the amygdala to influence retention (Gallagher, et. al., 1981; Sternberg and Gold, 1981). Also, epinephrine has been shown to be released at the time of training (Gold and McCarty, 1981). The more epinephrine released, the better the retention (McCarty and Gold, 1981). McGaugh (1983) writes, "It seems possible that motivation and reward may influence learning perhaps largely or perhaps only in part through the influences of hormones released by experience" (p.171).

Implications

Educational implications emanating out of information on memory systems must be viewed as tentative. As new information accumulates, new memory models will emerge. Even more significant to consider prior to listing implications is the cybernetic system which is operational in any classroom (Norman, 1985). Although models of the individual's information processing sequences exist, the interactive nature of classroom teaching must be considered. Classroom interaction includes influences on behavior as teacher interacts with each student and all students and as students interact with one another. At each instant, both teacher and individual student are shaping behavior in response to an ever-changing set of personal, classroom, and school descriptions. Social, cultural and environmental factors certainly affect the way we learn and remember. Perception itself is a complex component of memory. There is a strong interest currently in the ecological approaches to memory promoted by Gibson in the 1950's (Gardner, 1985). According to Norman (1985), several issues underlie the science of cognition, and they are each complex: belief systems, consciousness, development, emotion, interaction, language, learning, memory, perception, performance, skill, and thought.

With cognizance of the complex nature of cognition in general and memory systems in particular, we suggest the following list of questions which subsume a host of

potential implications for researchers and practitioners in science education.

1. Are there critical periods for encoding certain kinds of memory which need to be identified and related to future learning? This area could serve to underscore the significance of development in memory and to elaborate on the Piagetian stages and might be especially important in memory for procedural knowledge, including process and problem-solving skills.

2. How can memory for procedural knowledge be assessed? Since procedural knowledge manifests itself non-verbally, in the "doing" of the skill, effective means of assessing its acquisition at various stages of refinement is important. Error detection, remediation, and practice are needed to encode the skill successfully in memory.

3. Once an idea or skill has been stored in memory, how can it be altered, reorganized or even removed? The forgetting and/or restructuring of information is needed to replace misconceptions with sound ideas about how the world works. There is strong evidence supporting the intransigence of "alternative conceptions" in science. However, sound conceptual frameworks in the science disciplines must be built on a solid base of scientifically correct information.

4. Which teaching strategies or techniques enhance memory storage and retrieval? Association techniques, like mnemonies, are useful for storing certain types of declarative information. Cues are useful and even necessary for information retrieval. The identification of effective cues for designated ability groups continues to be a researchable area.

5. How does subconscious processing of information occur? Even though we are conscious of thinking about one idea at a given moment, a form of parallel processing appears to occur beneath the conscious level. A mechanism akin to "averted vision" in astronomical viewing of faint objects seems to occur. When the galaxy-gazer looks away from the galaxy itself, it is more clear than when it is viewed straight-on. In a similar manner when we stop "thinking" consciously about some elusive names or ideas, they often "pop into" view later on. There may be environments that enhance goal-directed subconscious processing of information.

6. What mechanisms explain storage of information under emotionally-charged conditions and retrieval of information under hypnosis and altered states of consciousness? The effects of "state" on memory prove

to be interesting and may yield findings in the mind's ability to focus and avoid interfering distraction.

7. How does the mind distinguish relevant from irrelevant information and what features of problems activate pattern recognition? Problem-solving requires recognizing the distinguishing features of the problem and matching those features to stored patterns. The ability to form new patterns is also indispensable in expanding one's knowledge base within a discipline.

8. How much information can be absorbed in a meaningful way in one course and during one academic year? Curriculum planners need to be aware of the time and practice needed to acquire procedural knowledge, especially.

9. How effective are intrinsic and extrinsic reward systems in activating memory? Preliminary findings on the biochemistry of memory suggest a relationship between memory and reward.

10. As we grow older, how can we preserve and even enhance our memories? Are there life-long learning techniques which should be incorporated into school curricula? Learning about learning, especially about one's own unique abilities to store and retrieve memories, will allow learning to continue beyond the formal classroom.

11. How does social interaction influence memory? The complex social system of the classroom may provide opportunities for structuring situations which improve memory by allowing students to consider the perspectives of others.

SUMMARY

In summary, this paper has provided a brief review of memory system findings from various fields which are known collectively as cognitive science. It has also suggested a number of questions with potential to impact science teaching.

We suggested a need for a three-step research-based program leading ultimately to classroom implications for science teachers. The paper is an introduction to step one. It is incumbent upon members of the science education community to enter into dialogue with one another and with researchers in cognitive science in order to plan the research studies which are the basis for step two. Then, cautiously, we proceed to step three, suggesting classroom implications to teachers. The clues we currently have about workings of human memory can be useful even now as we form hypotheses about effective teaching and learning environments. But our clues must be grounded in well-conceptualized research studies based on an ever-expanding theoretical base.

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